2002 REVIEW OF NEUTRON AND NON-NEUTRON NUCLEAR DATA

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ABSTRACT

Review articles are in preparation for the 2003 edition of the CRC's Handbook of Chemistry and Physics dealing with both non-neutron and neutron nuclear data. Highlights include: withdrawal of the claim for discovery of element 118; new measurements of isotopic abundances have led to changes for many elements; a new set of recommended standards for calibration of γ-ray energies have been published for many nuclides; new half-life measurements reported for very short lived isotopes, many long-lived nuclides and ββ decay measurements for quasi-stable nuclides; a new reassessment of spontaneous fission (sf) half-lives for ground state nuclides, distinquishing half-lives from sf decay and cluster decay half-lives and the new cluster-fission decay; charged particle cross sections, (n,p) and (n,α) measurements for thermal neutrons incident on light nuclides; new thermal (n,γ) cross sections and neutron resonance integrals measured. Details will be presented.

1. Introduction

The published literature is scanned and periodically evaluated for nuclear data. For non-neutron nuclear data, all pertinent information on the isotopic masses, atomic weights, isotopic composition, radioactive half-lives, alpha particle, beta, proton, positron, isomeric transition energy and branching ratios, gamma-ray energies and intensities, nuclear spin, parity, magnetic dipole and electrical quadrupole moments and other nuclear information are reviewed and "best values" are recommended and published in the Chemical Rubber Company's (CRC) Handbook of Chemistry and Physics review article "Table of the Isotopes"[1].

For neutron nuclear data, cross sections for thermal energy (room temperature) reactions, resonance integrals, scattering lengths and Maxwellian averaged neutron cross sections at an energy of 30 keV for astrophysical applications are reviewed and "best values" are recommended and published in the CRC's Handbook of Chemistry and Physics review article "Neutron Scattering and Absorption Properties"[2].

Recent changes in the recommended data and their significance will be discussed for both the non-neutron nuclear data and the neutron nuclear data. Cautions in applying these data will also be noted.

2. Elements and Nuclides

The most significant change in the past few years has been the claim of discovery for the element Z = 116 and the element Z = 118 in an April 1999 experiment at the Lawrence Berkeley National Laboratory (LBNL) and then the subsequent withdrawal of this claim in 2001, along with the supporting data because the original data could never be confirmed by LBNL or any other Lab. LBNL officials now allege the original discovery of these elements was based on fabricated research[3]. Independent research at the Flerov Joint Institute for Nuclear Research at Dubna and the Lawrence Livermore Laboratory has since claimed the discovery of a

different nuclide of element Z = 116. Although Dubna now notes[4] that a single atom of element 118 appears in their preliminary data, there is no claim made for element Z = 118, as yet. Thus, element Z =118 has to be removed from the list of known elements at this time.

There have been a number of new short-lived nuclides discovered, which are basically located far from the line of beta stability. In the past half dozen years, there have been 459 new nuclides to bring the total number of nuclides to 2975, which does not include electromagnetic isomers. The newly discovered nuclides have been found with 40% on the neutron deficient side of stability (lighter masses of an element) and 60% on the neutron excess side (heavier masses of that element). This ratio has not been systematic throughout the periodic table. For the light and medium weight elements up to Z = 70, 2 out of 3 new nuclides have been discovered on the neutron excess side, while for the heavier elements, Z>70, 3 out of 4 new nuclides have been found on the neutron deficient side of stability. For many of these nuclides, some radiation has been followed to allow an estimate of the radioactive half-life but in other cases only the existence of the nuclide from its mass and charge has been made.

3. Isotopic Composition of the Elements

Changes in the isotopic composition of the elements have an impact on the neutron activation of foils used in radiation dosimetry. The foil that is irradiated usually has a normal composition of the naturally occurring stable isotopes of that element. The reaction rate that is measured will depend on what the natural abundance is for the stable isotope undergoing the reaction in the foil. This is necessary information, whether a neutron is incident for (n,γ), (n,α) or (n,p) reactions and whether a neutron's energy is slow, intermediate or fast. Activation analysis is a special use of isotopic abundances. Abundances are normalized to unity so the number of significant digits in the major isotope often requires truncation in the number of significant digits (lost information) in the minor isotope, which is usually the one isotope of interest for activation purposes.

In recent years, the isotopic composition of the chemical elements have been revised to better fit the average properties for the elements. The philosophy is to examine the total range in nature of the abundance for each isotope of a given element and then to position the recommended value as the mid-point of this total range, independent of the values for the most common source of the element. One of the results is the much larger uncertainty assigned to the mean value compared to previous values. Hydrogen would be an example, where the deuterium content had previously been quoted for ocean water and fresh water with a value of 150 parts-per-million (ppm) and an uncertainty of 10 ppm. The deuterium abundance is now quoted as 115 ppm with an uncertainty of 70 ppm because the possible range of the deuterium values available in nature, now includes electrolytic hydrogen, where the deuterium content is 45 ppm. This isotopic fractionation effect is mostly seen among the light elements, where the processes of nature are mass dependent. The variations of isotopic abundance for selected elements have been reviewed recently[5]. The abundance values for some of the elements that have changed recently (either due to new measurements or to variations in the range) can be seen in Table 1. Many of the abundance changes have been very small or have only impacted the uncertainty in the abundance and not the abundance value itself. These types of changes are not listed in the Table below.

In the case of osmium as presented in the Table, it should be noted that the isotopic composition as it is listed applies only to an osmium source that has been in equilibrium with a rhenium parent over a very long period of time compared to the half-life of rhenium-187, i.e., 10^{10} years. The isotopic abundance values that are provided in the Table correspond to the best measurement of a single source of osmium. The beta decay of the rhenium-187 produces additional amounts of osmium-187. However, if a given osmium sample of interest was rhenium free, then the isotopic composition for that osmium sample would appear significantly different in terms of the abundance values. There would have been no rhenium-187 decay to osmium-187 and the abundance value of that osmium-187 would be reduced from 1.96 % to 1.6 % There would also be changes for the other osmium isotopes, generally leading to increased values.

Osmium is not the only element which benefits from radioactive decay of an isotope of another element. Strontium has been found in nature in a rubidium sample, where isotopic composition of strontium in the sample was 100 % for the strontium-87 isotope, rather than about 7.0 % strontium-87. This would be due to

Table 1. Revised Isotopic Abundance Values in Atom Percent for Some Elements

H-1	H-2						
99.9885	0.0115						
Li-6	Li-7						
7.59	92.41						
C-12	C-13						
98.93	1.07						
O-16	O-17	O-18					
99.757	0.038	0.205					
Si-28	Si-29	Si-30					
92.223	4.686	3.091					
S-32	S-33	S-34	S-36				
94.93	0.76	4.29	0.02				
Zn-64	Zn-66	Zn-67	Zn-68	Zn-70			
48.27	27.98	4.10	19.02	0.63			
Ge-70	Ge-72	Ge-73	Ge-74	Ge-76			
20.37	27.38	7.76	36.66	7.83			
Mo-92	Mo-94	Mo-95	Mo-96	Mo-97	Mo-98	Mo-100	
14.77	9.23	15.90	16.68	9.56	24.19	9.67	
Te-120	Te-122	Te-123	Te-124	Te-125	Te-126	Te-128	Te-130
0.09	2.55	0.89	4.74	7.07	18.84	31.74	34.08
Dy-156	Dy-158	Dy-160	Dy-161	Dy-162	Dy-163	Dy-164	
0.056	0.095	2.329	18.889	25.475	24.896	28.260	
Er-162	Er-164	Er-166	Er-167	Er-168	Er-170		
0.139	1.601	33.503	22.869	26.978	14.910		
Hf-174	Hf-176	Hf-177	Hf-178	Hf-179	Hf-180		
0.16	5.26	18.60	27.28	13.62	35.08		
Os-184	Os-186	Os-187	Os-188	Os-189	Os-190	Os-192	
0.02	1.59	1.96	13.24	16.15	26.26	40.78	

the beta decay of rubidium-87, which also has a radioactive half-life of about 10^{10} years. The strontium isotopic composition which is usually quoted is given for rubidium-free strontium, since there are many single sources of strontium for which the isotopic abundance values have been measured.

4. Radioactive Half-lives of Nuclides

The radioactive half-life is of interest to reactor dosimetry because the half-life of the product nucleus in a nuclear reaction has a direct impact on the determination of the reaction rates. For a given count rate, the reaction rate is inversely proportional to the half-life of the measured product nucleus. In recent years there has been a significant interest in the possible decay modes of the stable isotopes of the chemical elements.

For the very long-lived nuclides (many of which have always been considered stable isotopes) there have been recent attempts to determine the decay rate for exotic reactions such as proton decay, $\beta^-\beta^-$ decay, $\beta^+\beta^+$ decay, double electron capture decay, Ecβ^+ decay, as well as long-lived α decay and long-lived β^- decay. An

Table 2. Radioactive Half-lives and Decay Modes of Long-lived (Quasi-stable) Nuclides

Nuclide	Decay	Years	Nuclide	Decay	Years	Nuclide	Decay	Years
H-1	proton	$>4\cdot10^{23}$	Ca-46	β^- - β^-	$>4\cdot10^{15}$	Ca-48	β^-	$2.4\cdot10^{18}$
V-50	EC / β^-	$>14\cdot10^{16}$	Cr-50	β^+ - EC	$>18\cdot10^{16}$	Ni-58	EC-EC	$>4\cdot10^{19}$
Zn-64	EC - EC	$>8\cdot10^{17}$	Ga-71	β^-	$>35\cdot10^{25}$	Ge-73	β^-	$>26\cdot10^{22}$
Ge-76	β^- - β^-	$16\cdot10^{20}$	Se-82	β^- - β^-	$8\cdot10^{19}$	Kr-78	β^- - β^-	$>9\cdot10^{19}$
Rb-87	β^-	$49\cdot10^{9}$	Zr-94	β^- - β^-	$>1\cdot10^{17}$	Zr-96	β^-	$>17\cdot10^{17}$
Mo-92	β^+ - EC	$>3\cdot10^{17}$	Mo-100	β^- - β^-	$1.2\cdot10^{19}$	Ru-96	β^+ - β^+	$>31\cdot10^{15}$
Cd-106	β^+ - β^+	$>26\cdot10^{16}$	Cd-108	EC - EC	$>41\cdot10^{16}$	Cd-113	β^-	$77\cdot10^{14}$
Cd-116	β^- - β^-	$38\cdot10^{18}$	In-115	β^-	$44\cdot10^{13}$	Sn-124	β^- - β^-	$>22\cdot10^{17}$
Te-123	EC	$24\cdot10^{12}$	Te-128	β^- - β^-	$77\cdot10^{23}$	Te-130	β^- - β^-	$27\cdot10^{20}$
Xe-124	β^+ - β^+	$>1\cdot10^{17}$	Xe-134	β^- - β^-	$>11\cdot10^{15}$	Xe-136	β^- - β^-	$>8\cdot10^{20}$
Ba-130	β^+ - β^+	$22\cdot10^{20}$	Ba-132	β^+ - β^+	$13\cdot10^{20}$	La-138	EC - β^-	$11\cdot10^{10}$
Ce-136	EC - EC	$>7\cdot10^{13}$	Ce-138	EC - EC	$>9\cdot10^{13}$	Ce-142	β^- - β^-	$>16\cdot10^{16}$
Nd-144	α	$21\cdot10^{14}$	Nd-150	β^- - β^-	$1.7\cdot10^{19}$	Sm-147	α	$11\cdot10^{10}$
Sm-148	α	$7\cdot10^{15}$	Sm-149	α	$1\cdot10^{16}$	Gd-152	α	$11\cdot10^{13}$
Gd-160	β^- - β^-	$>13\cdot10^{16}$	Yb-176	β^- - β^-	$1\cdot10^{26}$	Lu-176	β^-	$38\cdot10^{9}$
Hf-174	α	$20\cdot10^{14}$	Ta-180	β^- - EC	$>12\cdot10^{14}$	W-180	α	$74\cdot10^{15}$
W-182	α	$83\cdot10^{17}$	W-183	α	$19\cdot10^{17}$	W-184	α	$40\cdot10^{17}$
W-186	α	$65\cdot10^{17}$	Re-187	β^-	$44\cdot10^{9}$	Os-184	α	$56\cdot10^{12}$
Os-186	α	$2\cdot10^{15}$	Pt-190	α	$45\cdot10^{10}$	Hg-196	α	$>1\cdot10^{14}$

evaluation of these reactions has been performed[6] and some of the results are listed in Table 2 above. The cutoff lifetime for inclusion in the Table was the stellar age[7]. If a nuclide has a half-life greater than the age of the universe, 12.5 billion years (10^9 y), it is listed.

Some of the upper limit values in the Table are due to ββ decay measurements and to the search for charge non-conservation (CNC), a violation of charge conservation, i.e., ^{71}Ga and ^{73}Ge β decays. β decay in ^{71}Ga is energetically forbidden but in CNC, no electron is emitted and its rest mass energy of 511 keV is available as extra decay energy. CNC decay energy is +275 keV, while it is -236 keV for the CC β decay. The ^{71}Ga solar neutrino experiments placed an upper limit of $3.5 \cdot 10^{26}$ years on this β decay[8], so CNC has not yet been observed. ββ decay can occur where β decay is energetically forbidden or strongly suppressed due to a large change of spin with little energy available. 2 electrons (and possibly 2 anti-neutrinos) are emitted. If there are no neutrinos (0ν) emitted, lepton number is not conserved. ν can be a Majorana particle (if identical to its anti-particle) or a Dirac particle (distinct from its antiparticle). For 0ν ββ decay, neutrinos must be Majorana particles while Dirac particles requires 2ν. Only 2ν ββ decays are listed in Table 2, since 0ν ββ decay have only had upper limits measured up to now. A recent measurement[9] claims to have observed a 0ν ββ decay

Table 3. Spontaneous Fission Branching Ratios in Percentage

Nuclide	Percent	Nuclide	Percent	Nuclide	Percent	Nuclide	Percent
Th-232	$1.2 \cdot 10^{-9}$	U-234	$1.6 \cdot 10^{-9}$	U-235	$7.0 \cdot 10^{-9}$	U-236	$9.4 \cdot 10^{-5}$
U-238	$5.4 \cdot 10^{-5}$	Pu-236	$1.9 \cdot 10^{-7}$	Pu-238	$1.8 \cdot 10^{-7}$	Pu-239	$3 \cdot 10^{-11}$
Pu-240	$5.7 \cdot 10^{-6}$	Pu-241	$2.4 \cdot 10^{-14}$	Pu-242	$5.6 \cdot 10^{-4}$	Pu-244	0.12
Am-241	$3.6 \cdot 10^{-10}$	Am-243	$3.7 \cdot 10^{-9}$	Cm-240	$3.9 \cdot 10^{-6}$	Cm-242	$6.4 \cdot 10^{-6}$
Cm-243	$5.2 \cdot 10^{-9}$	Cm-244	$1.4 \cdot 10^{-4}$	Cm-245	$6.1 \cdot 10^{-7}$	Cm-246	0.026
Cm-248	0.082	Cm-250	86.	Bk-249	$4.9 \cdot 10^{-8}$	Cf-237	10.
Cf-238	100.	Cf-240	≈2.	Cf-246	$2.3 \cdot 10^{-4}$	Cf-248	$2.9 \cdot 10^{-3}$
Cf-249	$4.4 \cdot 10^{-7}$	Cf-250	0.077	Cf-252	3.08	Cf-254	99.3
Cf-256	100.	Es-253	$8.9 \cdot 10^{-6}$	Es-255	$4.2 \cdot 10^{-3}$	Fm-244	100.
Fm-246	8.	Fm-248	0.10	Fm-250	$7 \cdot 10^{-3}$	Fm-252	$2.3 \cdot 10^{-3}$
Fm-254	0.059	Fm-255	$2.4 \cdot 10^{-5}$	Fm-256	91.9	Fm-257	0.21
Fm-258	100.	Fm-259	100.	Fm-260	100.	Md-245	100.
Md-247	100.	Md-259	≈100.	No-250	≈ 100.	No-252	32.
No-254	0.17	No-256	0.53	No-258	100.	No-260	100.
No-262	100.	Lr-253	1.3	Lr-259	20.	Lr-261	100.
Rf-253	≈100.	Rf-255	52.	Rf-256	99.7	Rf-258	87.
Rf-259	8.	Rf-260	100.	Db-255	≈ 20.	Db-260	9.6
Db-263	55.	Sg-258	100.	Sg-260	50.	Hs-264	50.

in ^{76}Ge with a half-life of $1.5 \cdot 10^{25}$ years, which implies lepton non-conservation and a mass for ν of 0.39 eV. Other researchers disagree and suggest this claim is based on flawed analysis of data.

5. Other Nuclear Information

This category of data would include α, β^-, β^+ and γ-ray energies and intensities, as well as branching ratios, for various modes of decay and nuclear moments and spins and parities. There has been a recent evaluation of γ-ray energy standards[10] for nuclides from ^{7}Be to ^{241}Am for energy calibration and there have been new measurements of the magnetic dipole moment and the electric quadrupole moment for a large number of isotopes for various elements. A total of 127 new dipole moments and 105 new quadrupole moments have been measured for the first time within the last 6 years. Measurements of moments for the two noble gases, krypton and xenon, account for 20% of all new nuclear moments in the Table of the Isotopes.

For heavy elements, there are other modes of decay (determining factors in stability), spontaneous fission (sf) decay[11] and cluster decay[12]. In sf decay, the nucleus breaks up into two approximately equal reaction products, both of which have very large masses (some 15 to 40 times larger than the α particle). Cluster decay is radioactive decay in which the emitted particle has a much smaller mass than a fission product but it is still larger than the alpha particle (some 3 to 8 times larger). There has also been a new "cluster-fission" or "primordial asymmetric fission" decay mode observed[13] for super-heavy elements, Z = 112 to Z = 122.

From the recent evaluation of sf half-lives, the sf branching ratios have been determined[14], where the sf branching ratio is the percentage of the time that a given nuclide decays by the sf mode compared to the total number of decays of that nuclide. Some of these branching ratios are presented in Table 3, above. Of the 124 sf nuclides, 45% have even protons (p) and even neutrons (n), 21% are even p - odd n, 18% are odd p - even n and 16% are odd p - odd n. For EE nuclides, early research implied a closed subshell at N=152 (peak in half-life values) but that disappears by rutherfordium (Z=104), as can be seen from Table 3.

For the very heavy chemical elements, a path to the super-heavy elements is being explored. In the process of this investigation, new nuclides and elements are continually being discovered. The addition and then the deletion of element 118 has led to some confusion in the list of the heaviest elements. The present list of the highest Z elements (Z > 109) and their nuclides is shown in Table 4 below.

Table 4. Nuclear Data on the Very Heavy Chemical Elements

Nuclide	Half-life	Mode	Energy	Nuclide	Half-life	Mode	Energy
^{292}116	≈ 33. ms	α decay	10.6 MeV	^{287}114	5. sec	α decay	10.3 MeV
^{288}114	≈ 1.8 sec	α decay	9.83 MeV	^{289}114	21. sec	α decay	9.71 MeV
^{277}112	0.48 ms	α decay	11.2-11.7	^{283}112	3. min	spon.fiss.	
^{284}112	9.8 sec	α decay	9.17 MeV	^{285}112	11. min	α decay	8.67 MeV
^{272}111	1.5 ms	α decay	11.0 MeV	^{267}110	≈ 3. μsec	α decay	11.6 MeV
^{269}110	0.17 ms	α decay	11.1 MeV	^{270m}110	≈ 6. ms	α decay	11.0-12.2
^{270g}110	≈ 10. μs	α decay	11.0 MeV	^{271m}110	≈ 1.1 ms	α decay	10.7 MeV
^{271g}110	≈ 56 ms	α decay	10.7 MeV	^{273m}110	0.76 ms	α decay	11.8 MeV
^{273g}110	118 ms	α decay	9.73 MeV	^{280}110	≈ 7.5 sec	spon.fiss.	
^{281}110	1.1 min	α decay	8.83 MeV				

6. Thermal Neutron Cross Sections and Resonance Integrals

Since the last edition of the Neutron Cross section book[15] (previously called BNL-325), there have been significant changes in many neutron cross section values. At thermal neutron energies, there are also a large number of charged particle reactions, such as the (n,p) and (n,α) reactions for a number of nuclides that had not previously been measured. In many cases, the target nuclide for the charged particle reaction is now radioactive. Some examples of these new charged particle cross sections as well as new or revised capture cross sections at thermal energies are given in the following Table 5 below. The cross section values are listed in units of barns (b) which is 10^{-24} cm^2 or in units of milli-barns (mb) = 10^{-27} cm^2. The uncertainty in the value is listed in parentheses following the value.

It can be noted that cross section and resonance integral values can vary significantly, if there is a large resonance in the thermal energy region. Measurements, which use a cadmium cover to separate these two quantities, can vary the effective neutron energy cutoff and lead to vastly different answers as in the cases of Am-241, 242m, Cd-113, Gd-155, 157, Sm-149. Using pointwise cross section data at 0.0253 eV and the integration over the neutron resonance energy region is a preferred method to cadmium ratios for extracting the thermal neutron cross section and the neutron resonance integral, respectively, in these cases.

Table 5. New or Revised Thermal Neutron Cross Sections

Nuclide	Reaction	σ (barns)	Nuclide	Reaction	σ (barns)
N-14	(n,p)	1.93(5)	O-17	(n,α)	0.257(10)
Ne-21	(n,α)	0.18(9) mb	Al-26	(n,p)	2.0(1)
Al-26	(n,α)	0.34(2)	Ar-37	(n,p)	37.(4)
Ar-39	(n,α)	0.1	Ca-41	(n,p)	7.(2) mb
Ti-44	(n,γ)	1.1(2)	Ti-44	(n,p)	< 0.2
Zr-91	(n,γ)	18.3(4) mb	Ho-166m	(n,γ)	$3.(1)\times10^3$
Ta-179	(n,γ)	$9.3(6)\cdot10^2$	Pb-206	(n,γ)	27.(1) mb
Pb-207	(n,γ)	0.61(3)	Pb-208	(n,γ)	0.23(1) mb

7. Discussion and Conclusions

Values for many of the parameters that are used in reactor dosimetry have changed over the years. In this review, the topics of newly discovered elements and nuclides, revised isotopic abundance values, some recent measurements of radioactive half-lives and new or revised measurements of neutron cross sections have been discussed. The impact of some recent measurements on some fundamental physics problems have also been examined. Finally, there was a discussion of some issues that users of these data should be aware of, when they select the above mentioned parameters for use in reactor dosimetry from various books or tables.

Conclusions include the search for charge non conservation reactions has led to only an upper limit on the half-life measurement and NO violation has yet been seen. A claim has been made from the 0ν ββ decay of ^{76}Ge that lepton number conservation has been violated and a mass of 0.39 eV for the neutrino has been finally been measured. Attempts to verify this measurement will no doubt be made. A new decay mode of cluster-fission for very heavy nuclides with emission of ^{208}Pb and the remaining cluster from the compound

nucleus has been claimed. Finally, element Z=118 that was claimed to have been discovered recently has now been retracted and element Z=116 is the heaviest element in the Periodic Table at the moment.

8. Acknowledgement

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9. References

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